

# NUCLEAR-CHARGE SPECTRA AND ENERGY SPECTRA IN THE SEPTEMBER 2, 1966, SOLAR-PARTICLE EVENT

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## ABSTRACT

Heavy nuclei ( $Z \geq 3$ ) were detected in the September 2, 1966, solar-particle event. This brings to five the number of events in which these particles have been detected. The proton energy spectrum was measured down to energies as low as 3 MeV and up to energies as high as 100 MeV, with measurements on the helium and heavier nuclei covering a more restricted range. The relative abundances of helium, light ( $3 \leq Z \leq 5$ ), medium ( $6 \leq Z \leq 9$ ), and heavier nuclei obtained in this experiment in the energy range from about 14 to 35 MeV nucleon<sup>-1</sup> agree with those measured in previous solar-particle events at higher energies and hence with those of the solar photosphere. This result strengthens the concept of a multicharged nuclear composition, which is a characteristic of solar-particle events. Use of the recent solar spectroscopic data and the ratio of helium to medium nuclei observed in the solar cosmic rays results in a hydrogen-to-helium ratio of  $16 \pm 2$ . An examination of the relative abundances of protons and medium nuclei shows that the propagation of solar particles in this event *cannot* be described by a simple diffusion model with a diffusion coefficient proportional to  $\beta$  or  $\beta R$ .

## I. INTRODUCTION

The Sun is now known to be a frequent emitter of energetic solar protons and alpha particles. Although nuclei with charges greater than 2 are rare, they have also been observed every time the intensity of an event was sufficiently great that one might expect to be able to detect them on the basis of their abundance in other events. Before the measurement to be reported here on the September 2, 1966, solar-particle event, heavy nuclei (nuclear charge  $\geq 3$ ) had been seen four times, in the events of September 3, 1960 (Fichtel and Guss 1961), November 12, 1960 (Biswas, Fichtel, and Guss 1962; Ney and Stein 1962; Yagoda, Filz, and Fukui 1961; Pomerantz and Witten 1962), November 15, 1960 (Ney and Stein 1962; Yagoda, Filz, and Fukui 1961; Pomerantz and Witten 1962; Biswas *et al.* 1963), and July 18, 1961 (Biswas, Fichtel, and Guss 1966). Upper limits have been set in other events (Biswas 1961), and also increases have been reported in the flux of heavy nuclei apparently unassociated with major flares (Kurnosova, Razorenov, and Fradkin 1962). An interesting result of the early measurements was that the multicharged nuclei with the same charge-to-mass ratio appeared to have the same composition each time it could be determined. Further, the composition seemed to reflect that of the Sun's photosphere insofar as measurements could be made. The helium and heavier nuclei, having a charge-to-mass ratio that is half that of the proton, can also be used to study solar-particle propagation in the interplanetary medium by comparing their abundance with that of the protons as a function of time.

In an attempt to expand our knowledge of the charge composition of the nucleonic component of the solar cosmic radiation and to make further studies of the characteristics of solar-particle propagation, SPICE (Solar Particle Intensity and Composition Experiment) was undertaken. The program is similar to the one undertaken in 1960, which led to the measurements of the relative abundances of the solar-particle events in 1960

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† The untimely death of Dr. Guss, who made a major contribution to the success of this program, prevented his participation in the final analysis.

(Fichtel and Guss 1961; Biswas *et al.* 1962; Biswas *et al.* 1963). Scientific sounding rockets were placed on stand-by at Fort Churchill in July 1966 to be shot into a solar-particle event, when one of sufficient intensity occurred. The first such event occurred on September 2, 1966.

This event was associated with a flare that began about 0538 U.T. on September 2, 1966, reached a maximum about 0600, and ended at about 930. It was reported as type 2B by Manila and type 3B by Anacapri (Italy). The flare occurred at  $23^{\circ}$  N.,  $55^{\circ}$  W. on the Sun and therefore was at a position on the Sun that was quite favorable for efficient propagation of particles from the Sun to the Earth along the lines of the roughly spiral interplanetary magnetic field. Three sounding rockets were fired into the event at the times given in Table 1, which also gives the approximate time from the maximum of the flare. This paper is aimed at a description of the results obtained in this event and a discussion of their relation to the study of the solar-particle phenomena mentioned above. This treatment will be preceded by a brief description of the SPICE payload and the techniques of data analysis.

TABLE 1  
EXPERIMENT FLIGHT TIMES

Flight	Time at Peak Altitude (U.T.)	Time from Flare Maximum
1	1443 September 2, 1966	8 <sup>h</sup> 7
2	2233 September 2, 1966	16 5
3	1733 September 3, 1966	35 5

## II. EXPERIMENTAL PROCEDURE

The nuclear-emulsion stacks flown in this experiment were located beneath the nose cone in the payload section of the Nike-Apache sounding rocket. The nose cone was extended to expose the stacks after the vehicle left the atmosphere and was retracted prior to re-entry. The duration of this exposure was approximately 250 sec; the extend and retract operations each took about 5 sec.

Two of the emulsion stacks were mounted on the sides of the vehicle with the emulsion face outward, so that particles entered normal to the emulsion surface. These stacks consisted of a single 200- $\mu$  pellicle and a lower section of twenty 600- $\mu$  pellicles, each of which was  $6.4 \times 7.1$  cm in area. As the nose cone extended and retracted, the lower section was displaced beneath the upper pellicle so that particles entering during the exposure could be unambiguously isolated. A third large stack of forty pellicles  $7.1 \times 13.8$  cm  $\times$  600  $\mu$  was located farther down the rocket axis with the normal to the emulsion surfaces along the direction of flight. The long dimension of the stack was approximately equal to the vehicle diameter, so that particles could be observed entering the pellicle edges at either end of the stack. This stack was used to observe the high-energy portion of the particle spectra.

Ilford G5 emulsion was used throughout. Twenty pellicles in the lower stack were underprocessed, however, to improve the grain-density discrimination between singly and doubly charged particles. The amount of material that intervened between the particle and the emulsion surface was 0.026 g cm<sup>-2</sup> (emulsion equivalent); this thickness determined the minimum detectable energy, which was 3 MeV for protons.

Proton spectra were obtained by making range measurements at low energies ( $\leq 12$  MeV) and from integral flux counts at various depths in the stacks at higher energies. Helium nuclei were resolved from protons by measurements of grain density versus

residual range. Heavier particles were resolved by counts of  $\delta$ -rays versus range, using a technique that has been described previously (Reames and Fichtel 1966). Owing to the very steep spectra in this event, the residual range of the heavy particles was too short to allow clear resolution of individual charges above  $Z = 6$ .

### III. RESULTS AND INTERPRETATION

The experimental results can be best understood by first presenting the energy spectrum of the various components during the three flights. A study of the energy spectrum is necessary background for the discussion of the composition and provides the basis for the considerations of solar-particle propagation. Therefore, this section will be divided into three parts, which will consider energy spectra, composition, and propagation.

#### a) *Energy Spectra*

In order to see the proton intensity level clearly and at the same time to observe the general variation of the energy spectra during the event, the three integral spectra for protons are shown in Figure 1. The intensity at low energies is large, the flux between 3 and 15 MeV being in excess of  $10^3$  protons (cm<sup>2</sup> sterad sec)<sup>-1</sup> for all three flights, but above 100 MeV it is quite small, of the order of 10 protons (cm<sup>2</sup> sterad sec)<sup>-1</sup> or less. The helium and medium nuclei also have steep energy per nucleon spectra, as shown in Figure 2. The spectra of helium and medium nuclei are even steeper than the proton spectrum, as shown in Figure 3. The integral spectra of medium nuclei in the two other exposures are similar to the first one, in that they are significantly steeper than the proton spectrum. They are then all steeper than the previous solar-flare particle events for which composition data exist, namely September 3, 1960, November 12 and 15, 1960, and July 18, 1961.

Returning specifically to the proton spectral data, there are several features worth noting. The spectra reflect the now well-established tendency for the particles of lowest energy to rise to their maximum and subside most slowly. This feature can best be shown by looking at the differential-rigidity spectra. Figure 4 shows that the fluxes of the particles of highest rigidity ( $\geq 250$  MeV) decrease with increasing time from the flare. At intermediate rigidities (about 150–200 MeV) the intensity was still increasing during the period from the first to the second flight but showed a decline from the second to the third flight. Below 120 MeV there is a progressive increase in particle intensity with time from the flare, with the exposure about 36 hours after the flare showing the maximum intensity.

Returning to Figure 2, notice that when the differential spectra for medium nuclei are multiplied by 60, the average ratio of medium to helium nuclei in previous events (Biswas and Fichtel 1965), the spectra agree within the errors with the spectral points for helium nuclei. The reason for the limited data on helium nuclei is the high proton-to-helium ratio, which makes the task of scanning for tracks of helium nuclei in the nuclear emulsion, following the tracks to the end, and identifying them a long, tedious one. However, the fact that the normalizing factor for multiplying the spectra of medium nuclei was selected from previous work makes the agreement quite significant, especially in view of the large variation from event to event of so many of the parameters associated with solar-particle events.

#### b) *Nuclear Composition*

One of the principal aims of the experimental series was to determine whether the composition of the multicharged nuclei is really the same in each event. The intensity of the September 2, 1966, event was very great at low energies but decreased quickly with increasing energy, as mentioned before; therefore, it was possible to obtain considerable information at low energies per nucleon but not at high energies, where the ranges of the particles are sufficiently great to allow good charge identifications. The

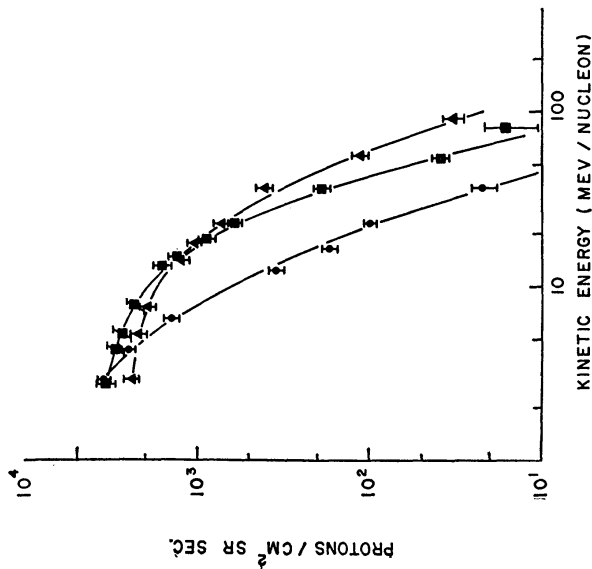


FIG. 1

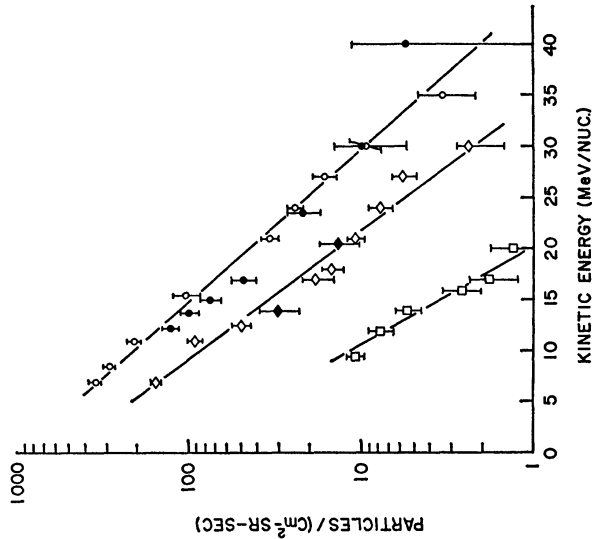


FIG. 2

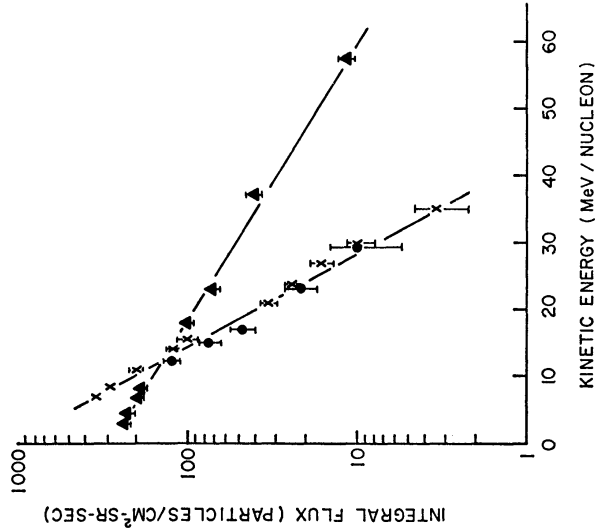


FIG. 3

FIG. 1.—Integral spectra for protons measured during the three sounding-rocket flights. Experimental points indicated by triangles, squares, and circles are for the first, second, and third flights, respectively. See Table 1 for the flight times.

FIG. 2.—Integral spectra medium and helium nuclei measured during the three sounding-rocket flights. Open symbols refer to data for medium nuclei multiplied by 60 and closed symbols to data for helium nuclei. Experimental points indicated by circles, diamonds, and squares refer to the first, second, and third flights, respectively. There is only one helium data point available in the third flight above 20 MeV nucleon<sup>-1</sup>, and it is not shown. See Table 1 for flight times.

FIG. 3.—Integral energy per nucleon spectra measured at 1443 U.T., September 2, 1966, for protons ( $\times 0.1$ ) (*triangles*), helium nuclei (*circles*), and medium nuclei ( $\times 60$ ) (*squares*).

experimental approach described earlier permitted the detection and identification of medium nuclei down to about 7 MeV nucleon<sup>-1</sup> rather than about 35 MeV nucleon<sup>-1</sup> as in the earlier experiments (Fichtel and Guss 1961; Biswas *et al.* 1962; Biswas *et al.* 1963; Biswas and Fichtel 1965). However, individual charge identification was not possible at these low energies; at higher energies, there were very few particles, and exact charge identification is difficult even then, because of the high background. Thus, although detailed charge measurements were not possible, the relative abundances of important charge groups, namely, helium and light, medium, and heavier nuclei, can be given.

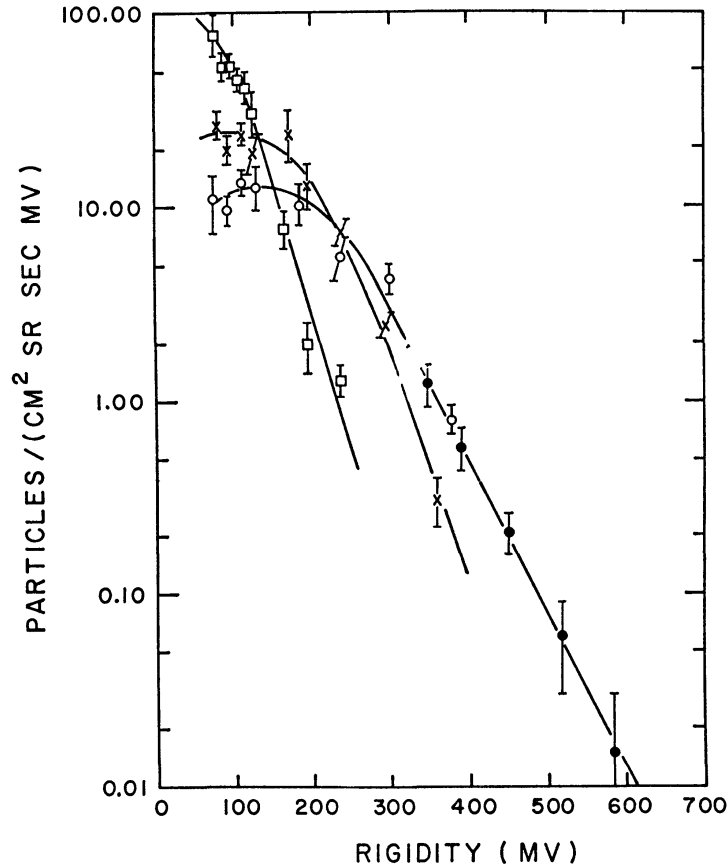


FIG. 4.—Differential-rigidity spectra for particles during the three sounding-rocket flights. Experimental points indicated by circles, crosses, and squares are for the first, second, and third flights, respectively. See Table 1 for flight times. All data are for protons, except the solid circles, which represent fluxes of helium nuclei.

Beginning with the ratio of helium to medium nuclei, it had already been shown that the energy spectra were similar and that the intensities appeared to be the same when the spectra of medium nuclei were multiplied by the average ratio of helium to medium nuclei obtained in previous work. To make these statements more quantitative, the ratios of helium to medium nuclei were found to be  $48 \pm 8$  in the energy interval from 12 to 35 MeV nucleon<sup>-1</sup> in the first flight and  $53 \pm 14$  in the energy interval from 14 to 35 MeV nucleon<sup>-1</sup> in the second. A summary of these and earlier measurements is given in Table 2. The error quoted for the average value of all the measurements assumes that this represents measurements of the same number.

There was no positive evidence for any light nuclei. A 3-sigma upper limit for the ratio of nuclei of charges 4 and 5 to the medium nuclei is 0.04, which is in agreement with previous, more severe limit of 0.02, set in the November 1960 events. There is also no positive evidence for the presence of lithium nuclei, but in that case no number will be quoted for the upper limit, since the exact efficiency for detecting these nuclei is difficult to determine. Since lithium is formed in the same general way as beryllium and boron, if the latter is not present the former is not likely to be either. The absence of light nuclei at these very low energies is not surprising because they are absent in the source, and it is not likely that the solar cosmic rays have gone through much material before reaching the Earth. Even if they have, the total probability for producing light nuclei below about 30 MeV nucleon<sup>-1</sup> is fairly small. The reasons for believing that the energetic solar particles have passed through very little material include the absence of

TABLE 2  
RATIO He/M OF HELIUM TO MEDIUM NUCLEI

Time of Measurements (U T)	Energy Interval $\Delta E$ (MeV nucleon <sup>-1</sup> )	(He/M) $\Delta E$	Reference
1408 September 3, 1960..	42 5- 95	68 $\pm$ 21	Fichtel and Guss (1961)
1840 November 12, 1960	42 5- 95	63 $\pm$ 14	Biswas, Fichtel, and Guss (1962)
1603 November 13, 1960	42 5- 95	72 $\pm$ 16	Biswas <i>et al.</i> (1962)
1951 November 16, 1960	42 5- 95	61 $\pm$ 13	Biswas <i>et al.</i> (1963)
0600 November 17, 1960	42 5- 95	38 $\pm$ 10	Biswas <i>et al.</i> (1963)
0339 November 18, 1960	42 5- 95	53 $\pm$ 14	Biswas <i>et al.</i> (1963)
1305-1918 July 18, 1961	120-204	79 $\pm$ 16	Biswas, Fichtel, and Guss (1966)
1443 September 2, 1966	12- 35	48 $\pm$ 8	Present work
2233 September 2, 1966	14- 35	53 $\pm$ 14	Present work
Weighted average of above readings	...	(59 $\pm$ 5)	
1225-2345 July 12, 1959	150-200	> 100 $\pm$ 35	Biswas (1961)
1030-1230 November 15, 1960...	175-280	$\approx$ 100 $_{-50}^{+100}$	Ney and Stein (1962)

light nuclei at higher energies in other events (Biswas *et al.* 1962; Biswas *et al.* 1963; Biswas and Fichtel 1965) and the failure to observe any indication of a significant decrease in the slope of the energy spectrum of solar protons down to energies as low as 3 MeV, which is not clearly an early-event propagation effect.

Because of the very steep energy spectrum, very few nuclei with charges of 10 or more could be clearly identified. Nonetheless, a ratio of neon to medium nuclei above 38 MeV nucleon<sup>-1</sup> of  $0.12 \pm 0.04$  was determined, where the quoted error reflects the charge-identification problem as well as the statistical limitations. This agrees with the average value for previous events of  $0.08 \pm 0.02$  (Biswas and Fichtel 1965). Some nuclei of clearly higher charges were observed, particularly in the low scans, as expected on the basis of the abundance of these elements in previous events, but charge-identification difficulties, and hence the inability to make energy measurements and a flux determination in a given energy interval, make it impossible to quote a quantitative relative abundance for those nuclei.

Thus, although the detailed conclusions that can be reached on charge composition are limited, the fact that at least the gross features of the composition of the multi-charged nuclei are the same as previous measurements gives added assurance that it is meaningful to speak of a composition of multicharged nuclei in solar-particle events. This feature is particularly remarkable in view of the large variations in so many of the other properties of solar-particle events, including size, energy spectra, relative abundances of electrons, protons, and helium nuclei, and time variations.

Recent spectroscopic results have shown with improved accuracy that the agreement between the spectroscopic measurements and the solar-cosmic-ray measurements of the composition of multicharged nuclei is still excellent, even within the narrower limits set by the more recent results. Table 3 summarizes these results.

c) Propagation

The study of the time variation of the relative abundances of two nuclear species, whose charge-to-mass ratios differ by a factor of 2, gives one a means of looking at the characteristics of solar-particle propagation in terms of its possible velocity or rigidity dependence. These measurements are particularly pertinent in determining whether the diffusion coefficient in the solar-wind diffusion model of solar-particle propagation

TABLE 3  
RELATIVE ABUNDANCES OF ELEMENTS

Element	Solar Cosmic Rays*	Solar Photosphere
<sup>2</sup> He	107 ± 12	
<sup>3</sup> Li		< 10 <sup>-5</sup> †
<sup>4</sup> Be- <sup>5</sup> B	< 0.02	< 10 <sup>-6</sup> †
<sup>6</sup> C	0.59 ± 0.07	0.60 ± 0.10‡
<sup>7</sup> N	0.19 <sub>-0.07</sub> <sup>+0.04</sup>	0.15 ± 0.05‡
<sup>8</sup> O	1.0	1.0‡
<sup>9</sup> F	< 0.03	0.001†
<sup>10</sup> Ne	0.13 ± 0.02	0.11§
<sup>12</sup> Mg	0.042 ± 0.011	0.051 ± 0.015
<sup>14</sup> Si- <sup>21</sup> Sc	0.090 ± 0.020	0.097 ± 0.03#
<sup>22</sup> Ti- <sup>28</sup> Ni	< 0.02	0.006†

\* Biswas *et al.* (1962); Biswas *et al.* (1963); Biswas and Fichtel (1965)  
† Goldberg, Müller, and Aller (1960); Aller (1961).  
‡ Lambert (1968).  
§ Lambert (1967a).  
|| Lambert and Warner (1968a)  
# Lambert and Warner (1968b).

(Parker 1956; Parker 1963; Krimigis 1965; Axford 1965; Reid 1964; Fibish and Abraham 1965; Roelof 1966) can be expressed with a simple velocity and rigidity dependence or whether a more complex picture must be used. In general, the diffusion coefficient is the product of the particle velocity and some function of the particle rigidity, which depends on the nature of the magnetic fields. In principle, this dependence on rigidity could be simply a constant, that is, propagation could be independent of particle rigidity. Evidence for this purely velocity-dependent mode of propagation has been seen in some events, e.g., November 12, 1960 (Biswas *et al.* 1962), and September 28, 1961 (Bryant *et al.* 1965). Evidence in other events speaks against this simple mode. One of the best examples of an event that does not have this characteristic is the one under discussion here. Figure 5 shows that the ratio of protons to medium nuclei in a given energy per nucleon, and hence velocity, interval varies greatly with time. Clearly, if the propagation were a purely velocity-dependent one, this ratio would be independent of time in the event.

Another dependence that has been suggested recently is a mean free path that is proportional to rigidity and hence a diffusion coefficient that is proportional to  $\beta R$  (Gloeckler and Jokipii 1966). This possibility is also excluded by the results of this event, as shown in Figure 6. It is seen that the ratio of the flux of protons to that of medium

nuclei in the same  $\beta R$  interval varies by a factor of 3 from the first to the last flight. Thus, neither of the two simplest possibilities proposed for the diffusion coefficient is correct in this event.

#### IV. SUMMARY

The study of the particle characteristics of the energetic hydrogen, helium, light, medium, and heavy nuclei in the September 2, 1966, solar-particle event confirmed many aspects that appear to be characteristic of these phenomena. There are, however, two features that deserve particular attention: the evidence in support of a characteristic composition of multicharged nuclei, which is independent of the solar-particle event, and the complete lack of agreement between the results and those predicted by a diffusion coefficient proportional either to  $\beta$  or to  $\beta R$ .

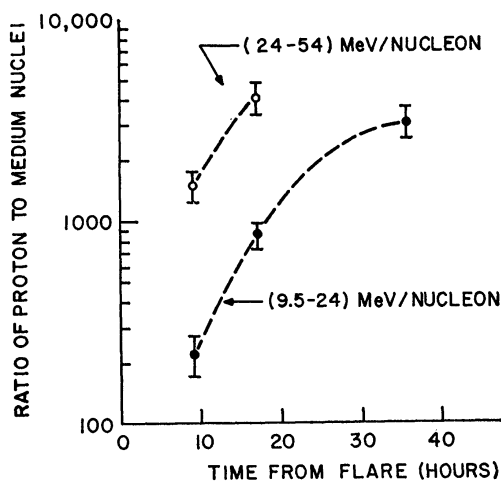


FIG. 5

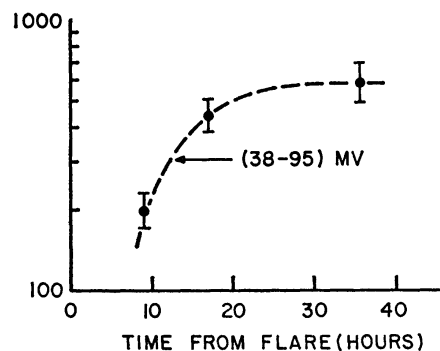


FIG. 6

FIG. 5.—Ratio of protons to medium nuclei for the three flights for the two different energy per nucleon intervals, which are specified in the figures, plotted as a function of time from the flare.

FIG. 6.—Ratio of protons to medium nuclei for the three flights for the  $\beta R$  (velocity in units of the velocity of light times particle rigidity) interval shown in the figure, plotted as a function of time from the flare.

As mentioned before, the measurement of a ratio of helium to medium nuclei that agrees with those measured in the four previous events of the last solar cycle in a different energy per nucleon interval gives strong support to the concept that the relative abundances of the multicharged nuclei are always the same. In this event, this was substantiated further by the measured ratio of neon to medium nuclei, the absence of light nuclei, and the agreement between the shapes of the spectra of helium and medium nuclei. As we have noted in previous articles (e.g., Biswas and Fichtel 1965), this is a factor that any accelerating mechanism must explain; further, this feature provides the tantalizing possibility of making very good measurements of the composition of the region of the Sun from which these particles come. It was shown that the composition of the energetic multicharged solar nuclei within the errors of present measurements agrees with measurements made for the Sun's photosphere and hence, as indicated previously (Biswas *et al.* 1963; Biswas and Fichtel 1965), gives a means of estimating the Sun's helium abundance. Using the recent solar spectroscopic data quoted by Lambert (1967b) for the relative abundances of carbon, nitrogen, oxygen, and hydrogen in the photosphere and the ratio of helium to medium nuclei obtained here, a hydrogen-to-helium ratio of  $16 \pm 2$  is obtained.

The results of the measurements reported here showed clearly that this event could not be described by a simple diffusion model with the diffusion coefficient proportional to  $\beta$  or  $\beta R$ . This result adds to a growing body of evidence that indicates the need for a more complex picture of solar-particle propagation—probably one that includes anisotropic diffusion with the possibility of a complex rigidity dependence for the diffusion tensor, the possibility of time dependence of the interplanetary medium, and probably the dependence of the diffusion coefficient on position.

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